Truck Platoon Load Effects on Oregon Bridges (ODOT Research Project SPR-848)

Session 18 Presentation

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NW Transportation Conference

Corvallis, OR

Oregon State University | Portland State University

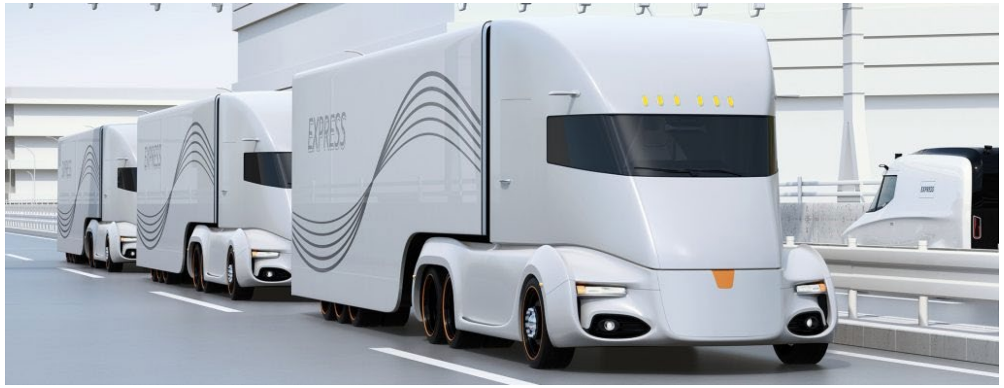
Overview of presentation

- Motivation and background
- Analysis of OR NBI database
- Structural analysis
- Big picture results
- Variable studies
- Case studies
- Summary and conclusions

Motivation for research

Truck platooning allowed on Oregon's transportation network due to recently passed House Bill 4059, Section 40, (c) and (d), which effectively waives headspace requirements for vehicles with "connected automated braking systems".

Source: https://talkbusiness.net/2017/04/truck-platooning-soon-to-be-seen-on-arkansas-interstates



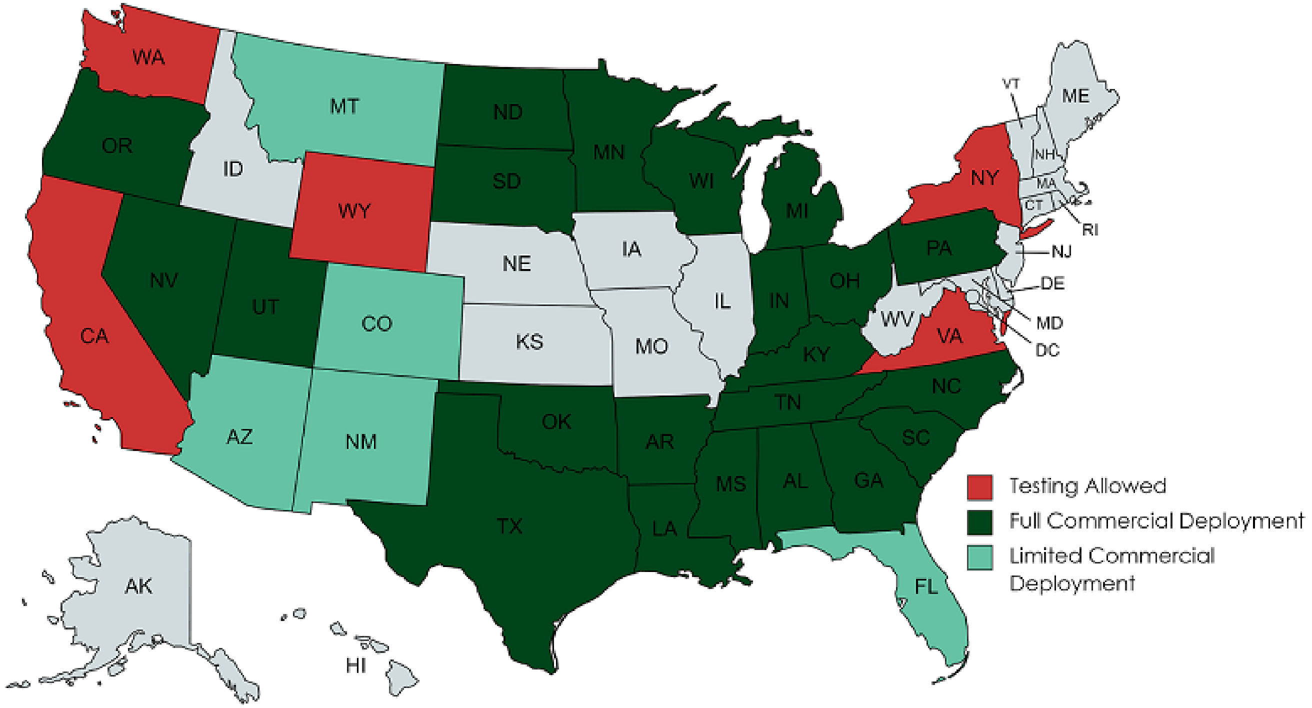
Where are we headed and what does this mean for Oregon's bridges?

Source: https://blogs.3ds.com/delmia/the-science-of-drafting-from-racing-to-truck-platooning

Motivation for research (cont.)

8/2020: Locomation & Wilson Logistics Perform Regular Autonomous Freight Deliveries in Groundbreaking Pilot Program

Source: https://www.businesswire.com/news/home/20200812005021/en/Locomation-Wilson-Logistics-Perform-Regular-Autonomous-Freight-Deliveries-in-Groundbreaking-Pilot-Program



Source: Bishop, 2020.

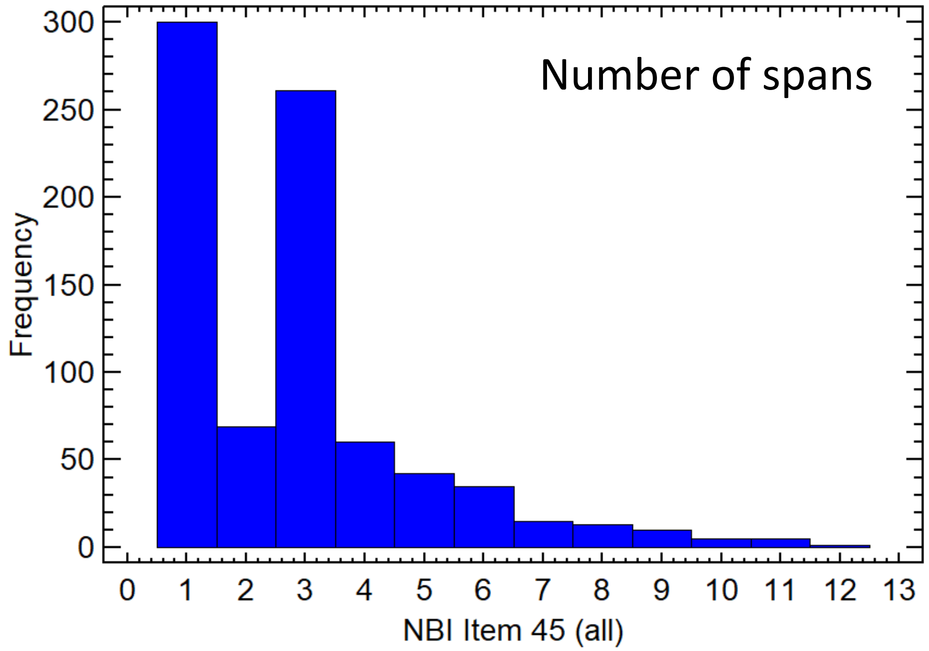
SPR-848 Research objectives

- Review and determine possible combinations of truck platooning configurations (axle weights and spacings, number of trucks, head spacing)
- Determine representative bridge span configurations (one, two, three span, relative span lengths)
- Determine internal forces on representative bridges due to possible platoon configurations and compare the internal forces with those caused by current vehicles loads considered by ODOT
- Use high performance computing to perform many line girder analyses and produce data sets for future studies

The results and findings of this project will allow for the creation of a set of policy and regulatory recommendations for freight mobility regulation, refined load rating of existing bridges, and recommendations for live load factors for future load ratings.

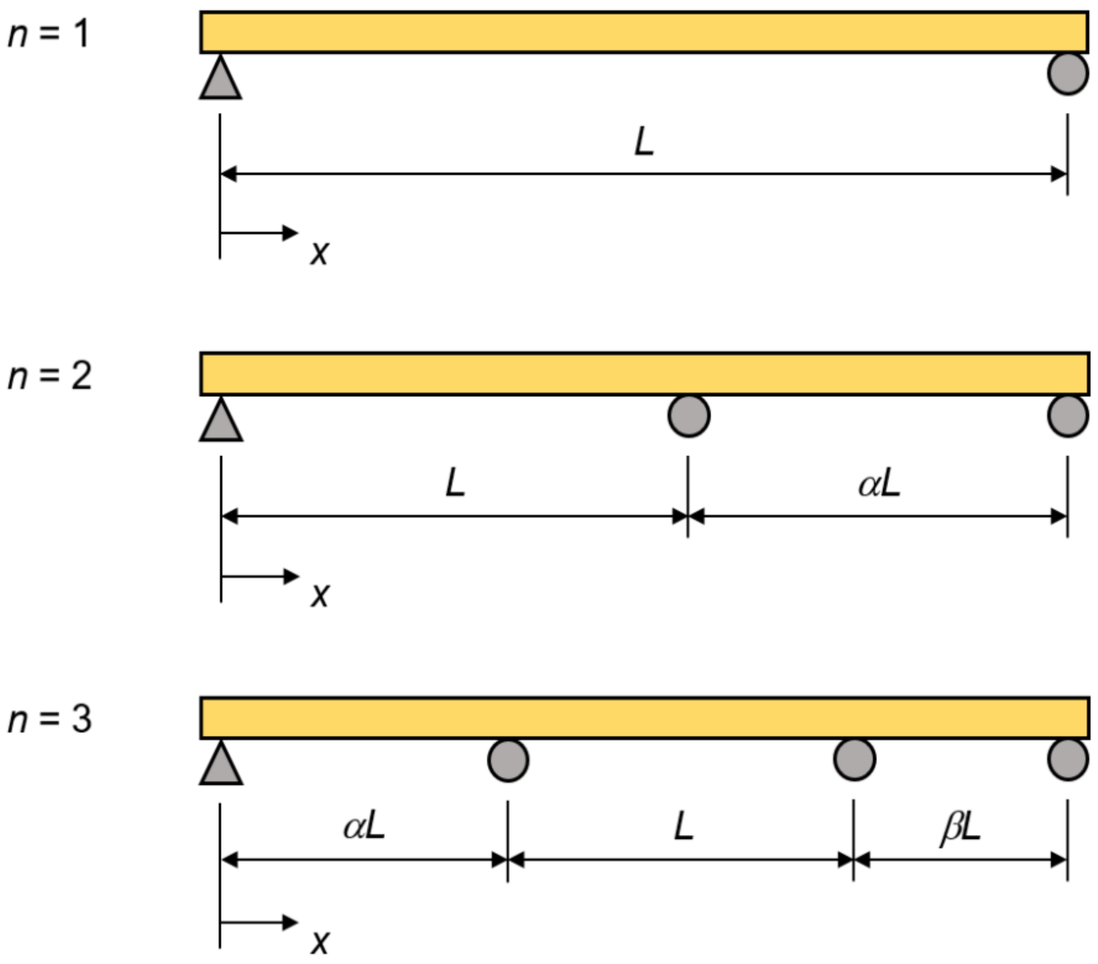
Representative bridges

- Searched NBI dataset for bridges in Oregon, total of 8214 bridges
- The “most typical” bridges in the dataset has the following characteristics:
  - Built in the early 1960s, i.e., is 55 to 60 years old
  - Designed based on HS 20 live load model
  - No skew, i.e., skew angle = 0 Degrees
  - Prestressed concrete (followed by reinforced concrete)
  - Stringer/multi-beam or girder structural system (followed by slab)
  - One or three spans (followed distantly by two, four, five, six, etc.)
  - Length of the maximum span, L = 12 to 16 m (for all bridges), and
  - bridges with one span (36% of all bridges): L = 12 to 16 m
  - bridges with two spans (8.3% of all bridges): L = 36 to 40 m
  - bridges with three spans (31% of all bridges): L = 12 to 16 m
  - bridges with four spans (7.2% of all bridges): L = 12 to 16 m
  - bridges with five spans (5.0% of all bridges): L = 20 to 24 m
  - Deck and superstructure condition rating of “7” (= good condition) followed closely by “6” (= satisfactory condition)
  - Rating of 25 to 30 tons and 20 to 25 tons, respectively



Representative bridges (cont.)

- For this project, 749 bridge models employed
  - Single-span with *L* = 15 to 65 m (in steps of 5 m) – 11 cases
  - Two-span with same *L* = 25 to 75 m (in steps of 5 m) and *a* = 1.0 to 0.75 (in steps of 0.05) – 66 cases
  - Three-span with *L* = 15 to 80 m (in steps of 5 m), α = 1.0 to 0.75 (in steps of 0.05), and β = 1.0 to 0.65 (in steps of 0.05) – 672 cases

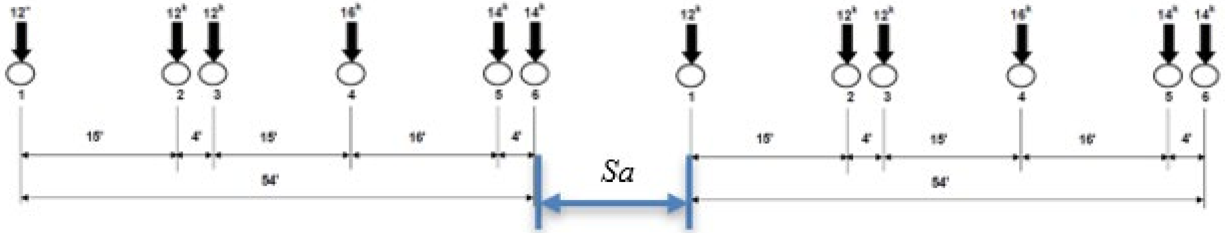


Live loads considered

- 37 vehicle live loads
  - Design live loads (18) - AASHTO LRFD HL-93 tandem plus HS-20 truck with axle spacings 14-30 ft
  - Oregon legal trucks (3) - **Type 3, 3S2, and 3-3**
  - Oregon specialized hauling vehicles (SHVs) (4) - SU4, 5, 6, and 7
  - FAST Act emergency vehicles (EVs) (2) - EV2 and EV3
  - Oregon continuous trip permit (CTP) trucks (3) - **CTP-2A, 2B, and 3**
  - Oregon single trip permit (STP) trucks (7) - STP-3, 4A, 4B, 4C, 4D, 4E, and 5BW

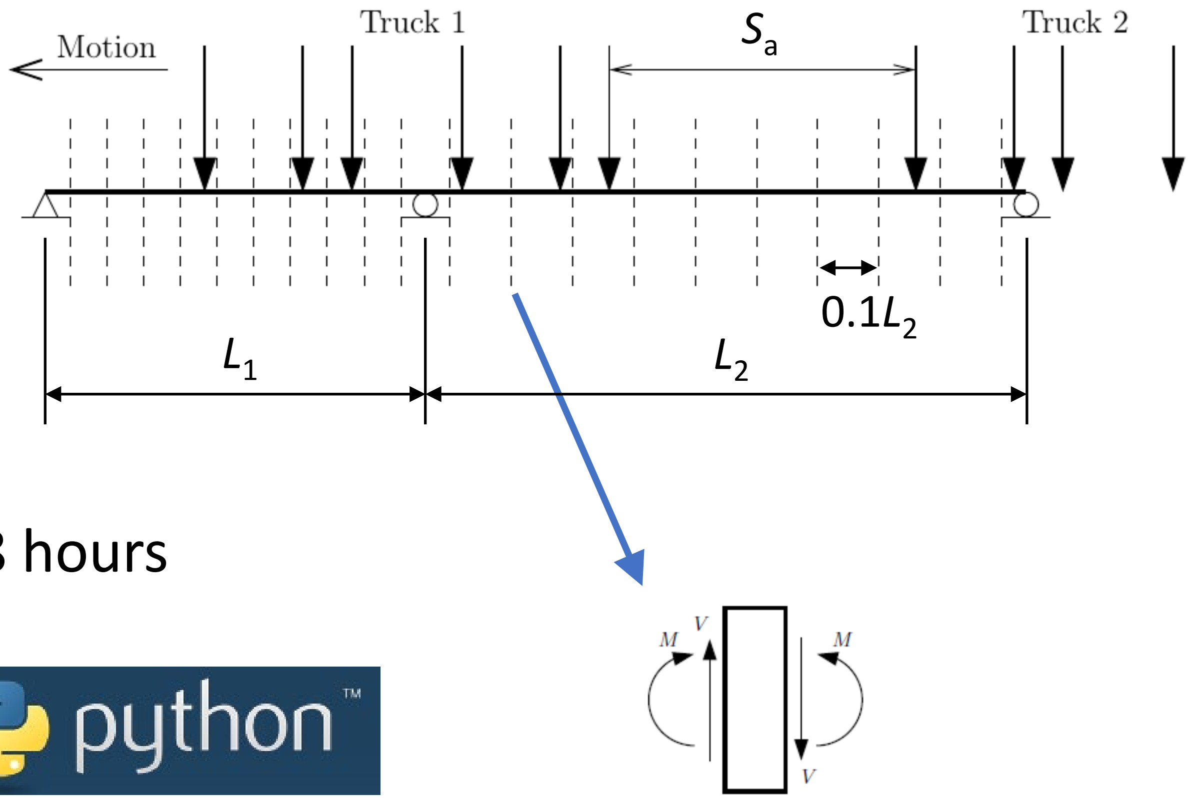
- Moving load analyses
  - Single truck
  - Truck platoon configurations
    - Two vehicles with head spacings 10 to 60 ft
    - Three vehicles with head spacings 10 to 60 ft

e.g., two OR Type 3-3 Legal trucks



Structural analyses

- 481 live load configurations and 749 bridge models = 360,269 analysis cases
- Sweep live loads both directions
- Move live loads in 1 ft increments
- "Embarrassingly parallel" analysis
  - Use OpenSees on Amazon Web Services
  - Python scripts
  - c6a.48xlarge instance with 192 vCPU
  - Reduce analysis time from weeks to about 8 hours

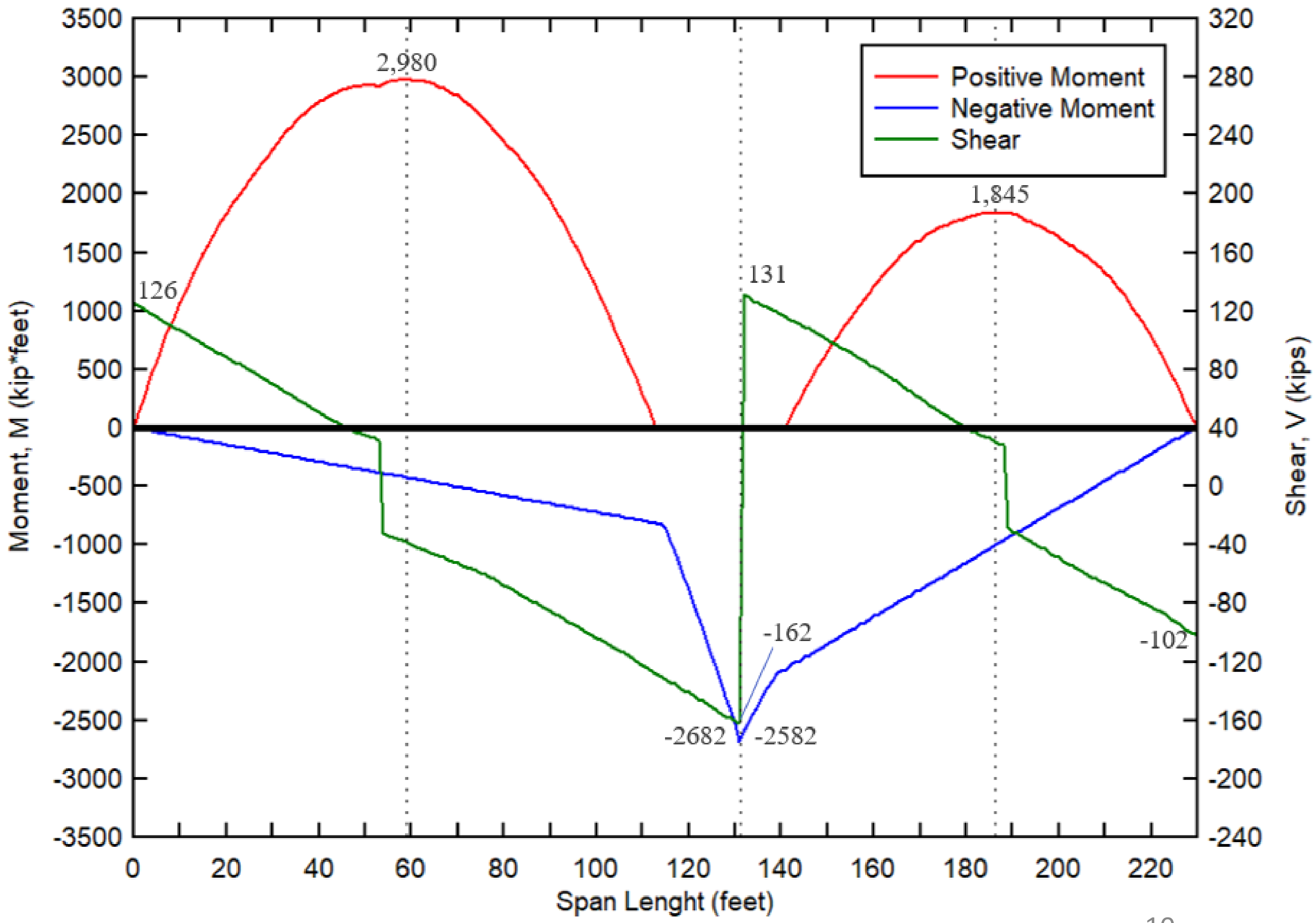


OpenSees python

https://pypi.org/project/openseespy/

Structural analyses (cont.)

- Record internal M,V at 0.1*L* locations along each span
  - Max *M*+ and coincident shear, *V*
  - Max *M*- and coincident shear, *V*
  - Max *V* and coincident moment, *M*
- From each of these envelopes, maximum values extracted for further processing

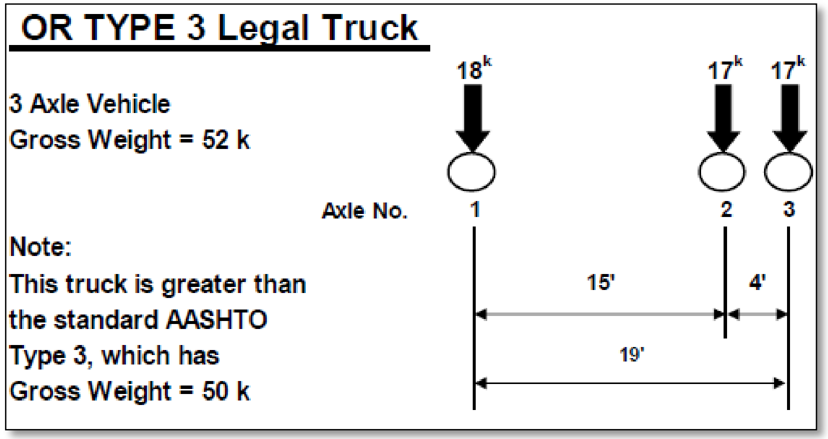


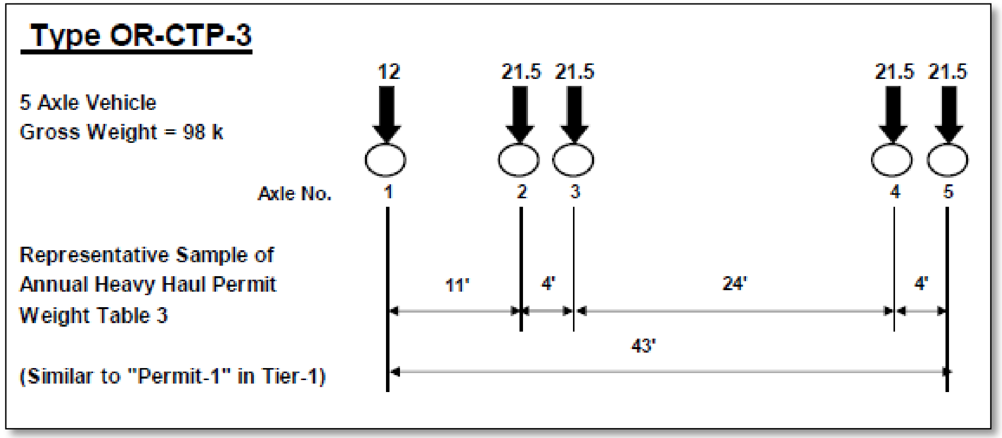
Big picture – Ratio distributions

Live load effect ratios:

$$Ratio = \frac{Internal\ Force\ of\ Specific\ Platooned\ Truck\ Type}{Internal\ Force\ of\ Single\ Reference\ Truck\ (OR\ Type\ 3\ or\ 3S2\ Legal)}$$

Reference vehicles:



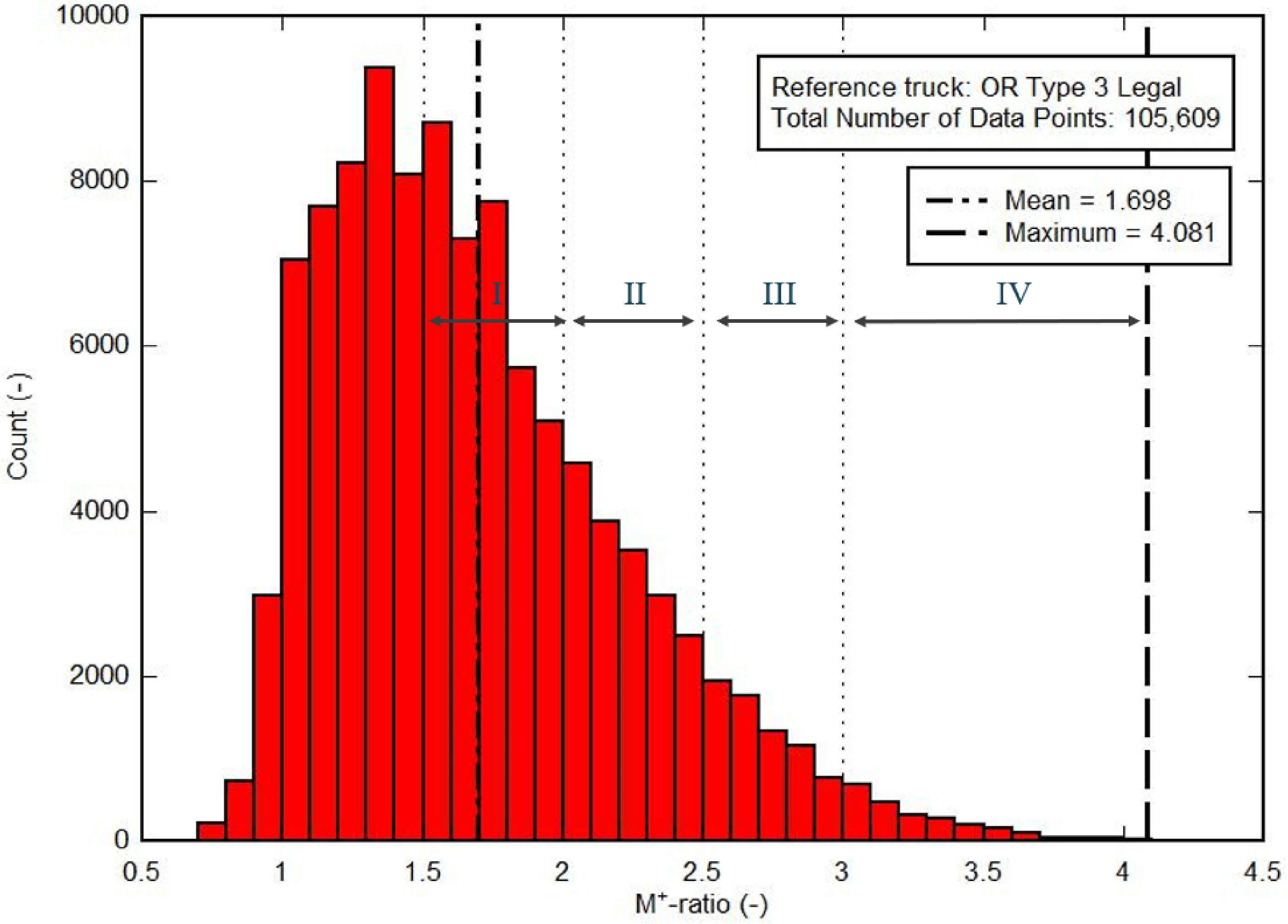


Big picture – Ratio distributions (cont.)

Ratios for Max *M*+

(Ref.: OR Type 3 Legal)

(All data)

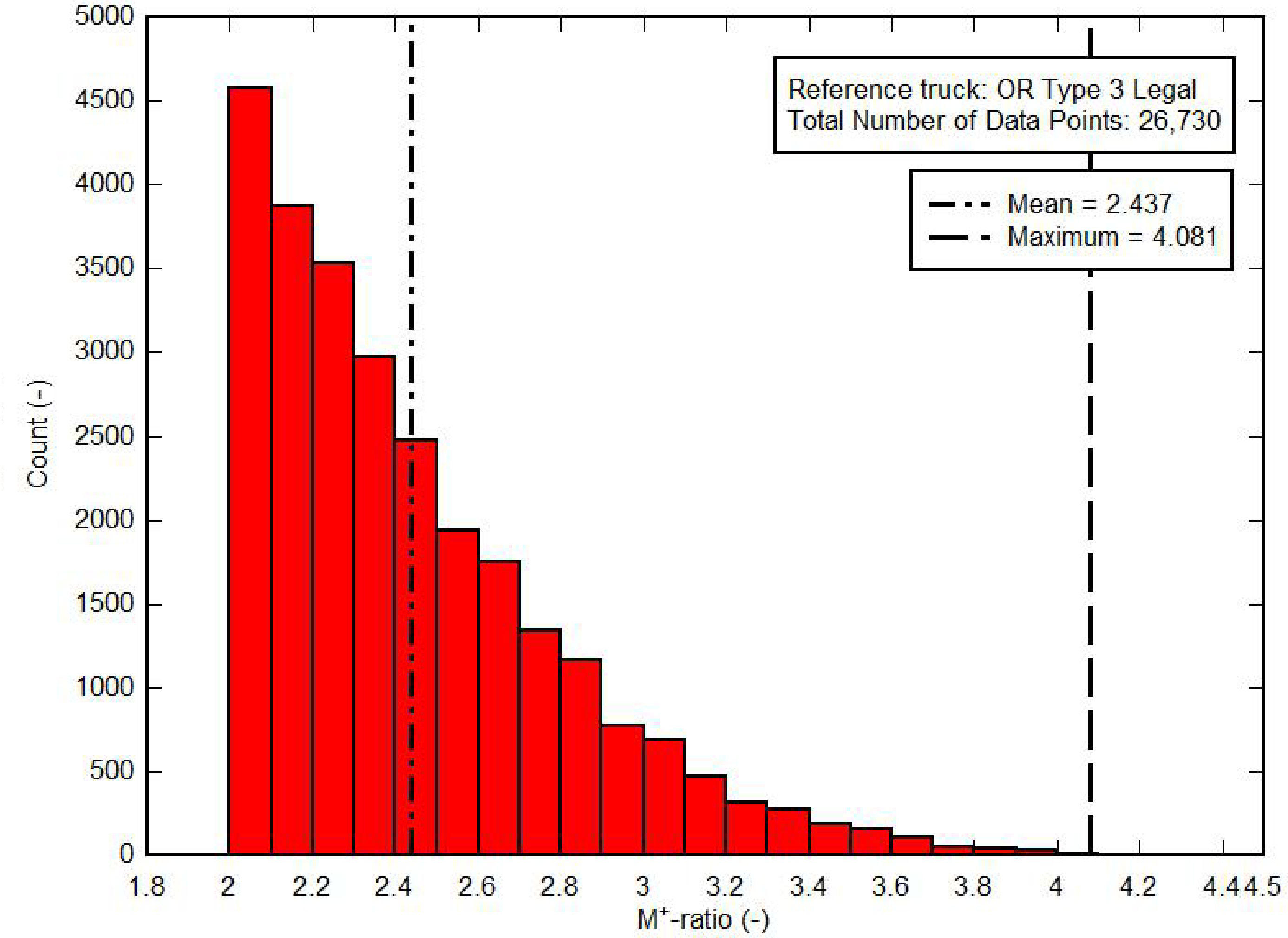


Big picture – Ratio distributions (cont.)

Ratios for Max *M*+

(Ref.: OR Type 3 Legal)

(Ratios > 2.0)

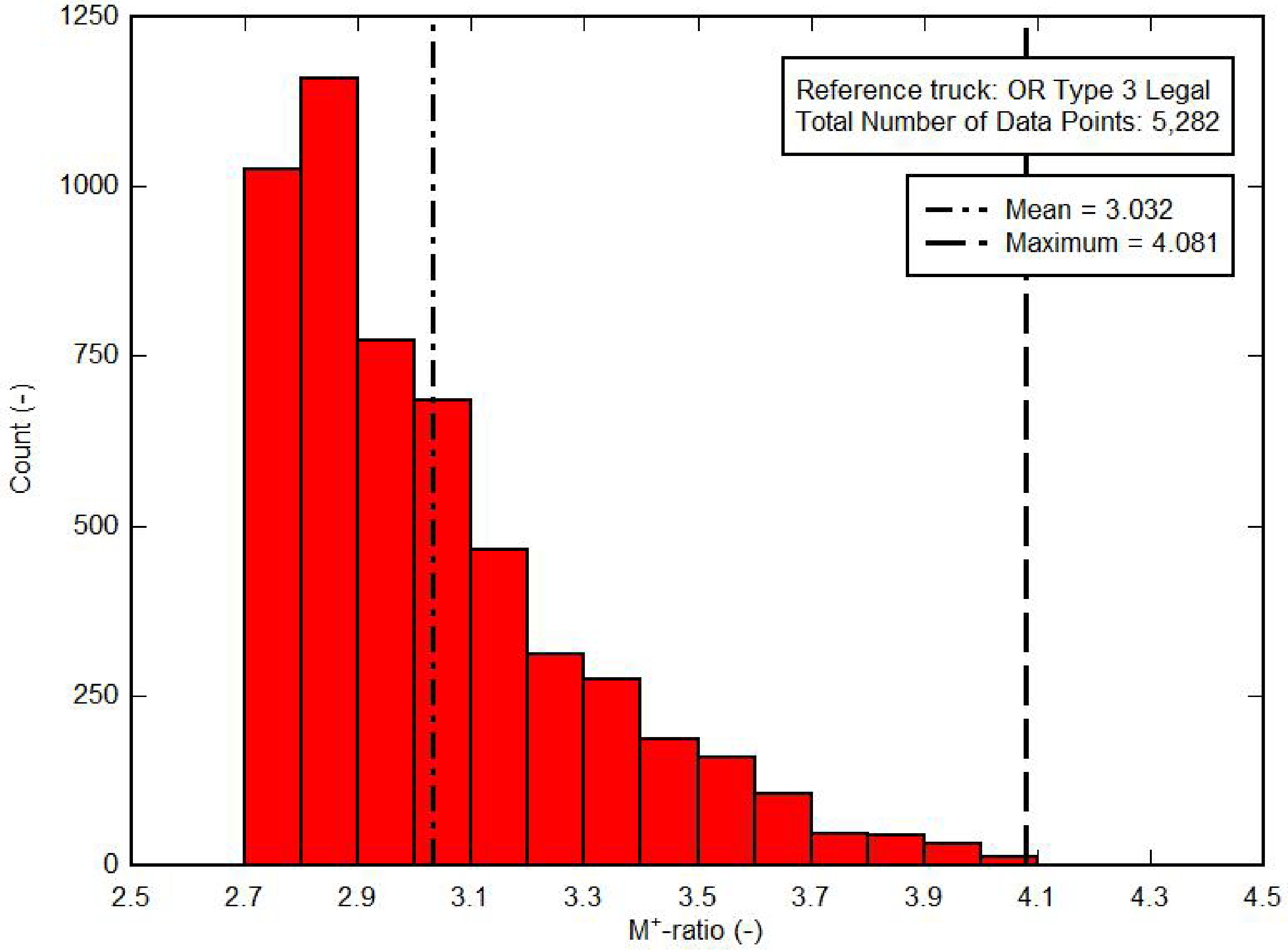


Big picture – Ratio distributions (cont.)

Ratios for Max *M*+

(Ref.: OR Type 3 Legal)

(95^{th} percentile)

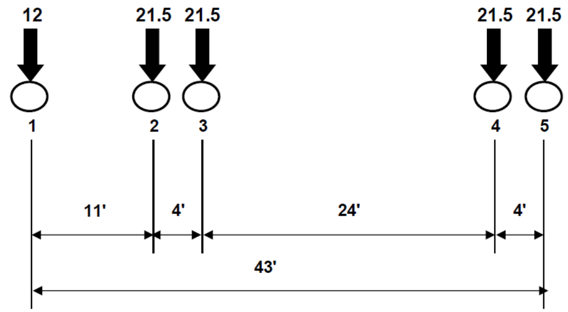


Big picture – Platoon configurations

Ratios for Max *M*+

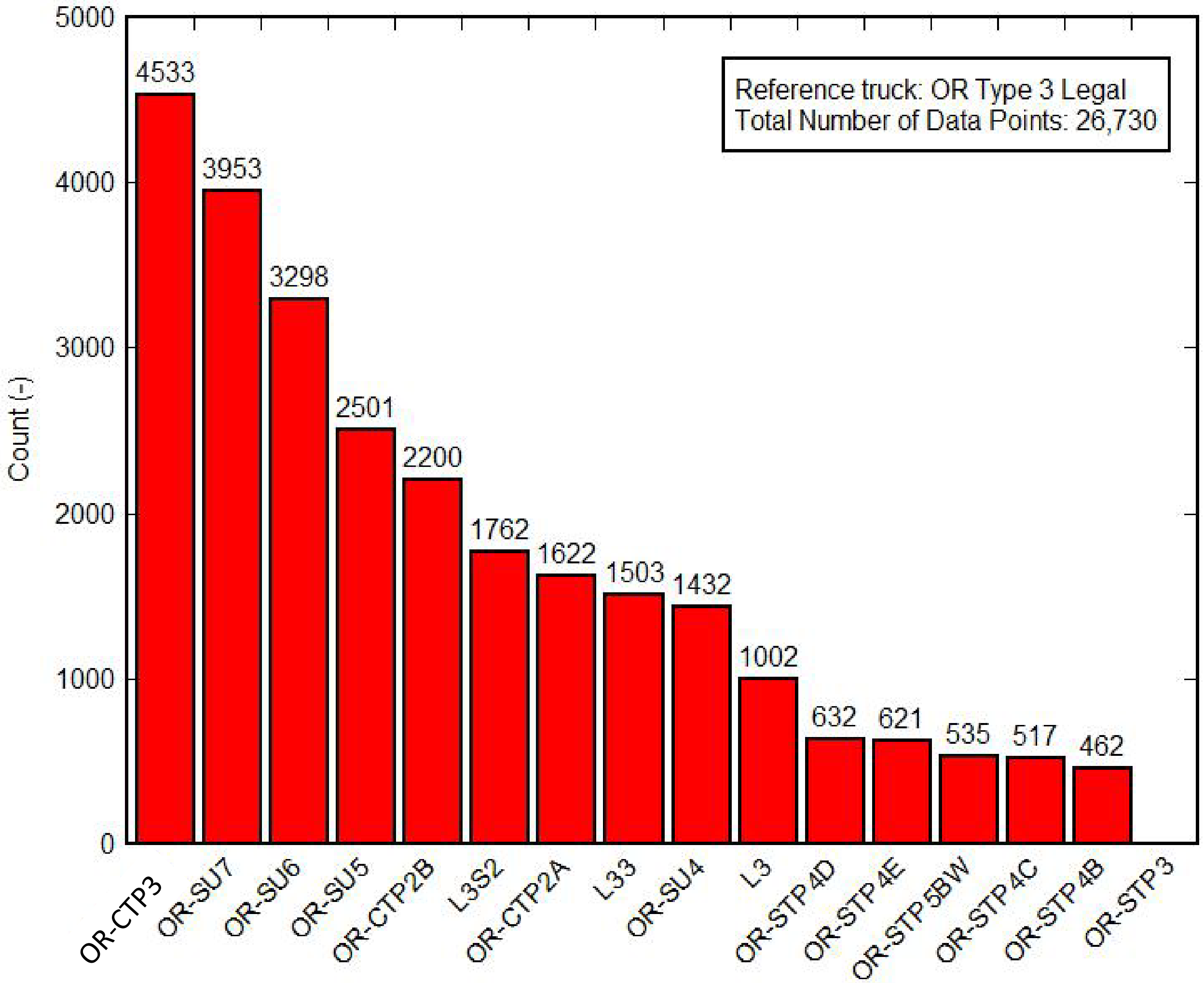
(Ref.: OR Type 3 Legal)

(By truck type, Ratio > 2.0)



Type OR-CTP-3
(GW: 98 kip)

OR-SU7 Legal
(GW: 97.5 kip)



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Big picture – Platoon configurations (cont.)

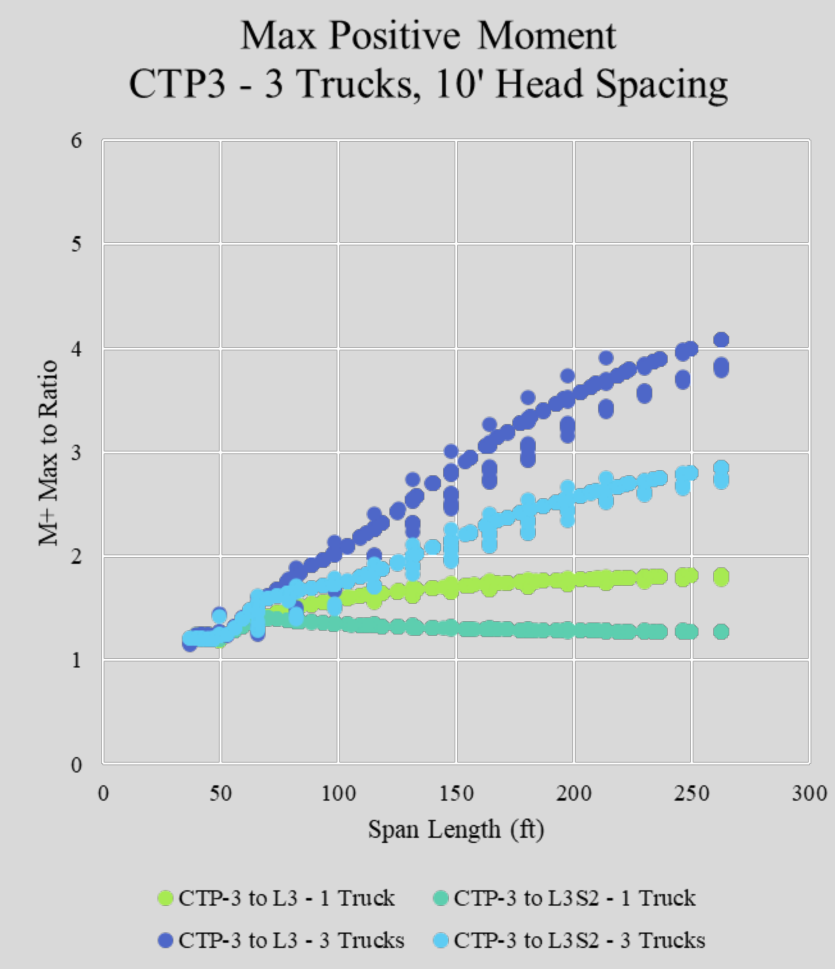
Ratios – Reference: OR Type 3 Legal

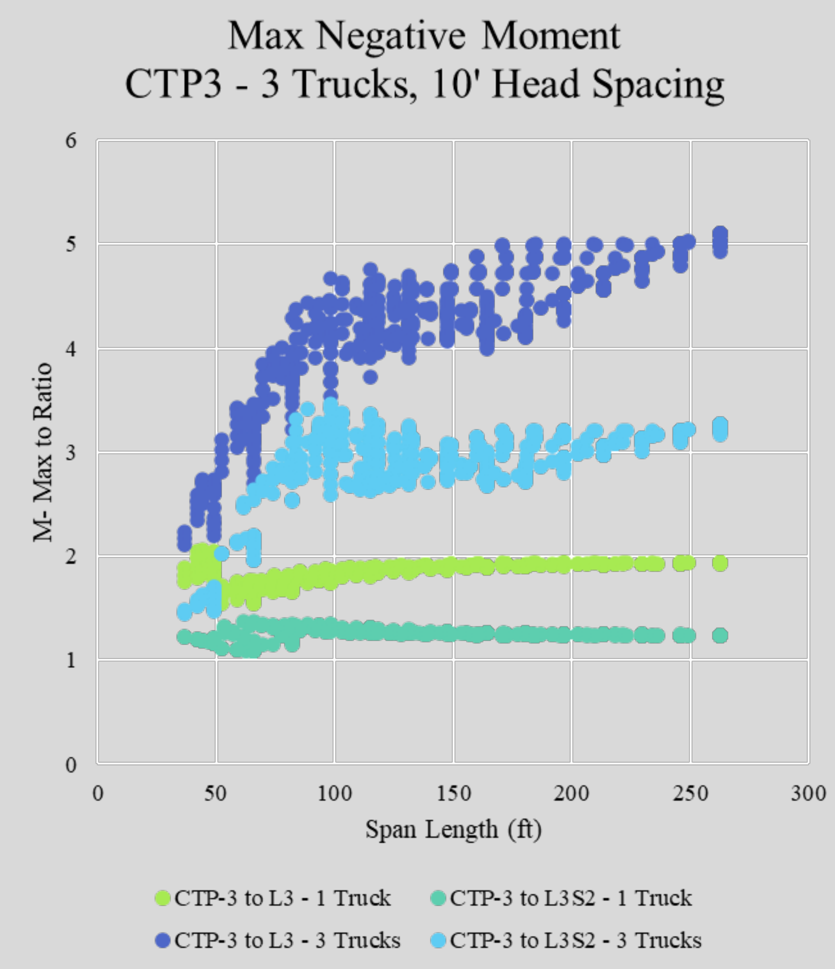
Maximum Positive Bending Moment		Maximum Negative Bending Moment		Maximum Shear	
Truck Type	*Ratio*	*Truck Type*	*Ratio*	*Truck Type*	*Ratio*
CTP3_3_10	4.08	CTP3_3_10	5.10	CTP3_3_10	4.77
CTP3_3_20	3.75	CTP2B_3_10	5.07	CTP3_3_20	4.54
SU7_3_10	3.66	CTP2B_3_20	5.04	CTP3_3_30	4.30
CTP3_3_30	3.43	CTP2B_3_30	5.01	SU7_3_10	4.08
SU6_3_10	3.39	CTP2A_3_10	4.97	CTP3_3_40	4.05
SU7_3_20	3.39	CTP2B_3_40	4.97	CTP2B_3_10	3.98
CTP3_2_10	3.19	CTP2A_3_20	4.95	SU7_3_20	3.92
CTP2B_3_10	3.15	CTP2A_3_30	4.92	CTP3_3_50	3.79
SU6_3_20	3.14	CTP2B_3_50	4.89	CTP2A_3_10	3.79
SU7_3_30	3.12	CTP2A_3_40	4.86	SU6_3_10	3.75
SU5_3_10	3.12	CTP3_3_20	4.82	SU7_3_30	3.75
CTP3_3_40	3.12	CTP2B_3_60	4.75	CTP2B_3_20	3.72
Legal3S2_3_10	3.08	CTP2A_3_50	4.74	Legal3S2_3_10	3.65
CTP3_2_20	3.02	CTP3_3_60	4.62	Legal33_3_10	3.61
Legal33_3_10	2.99	CTP3_3_30	4.62	SU6_3_20	3.61
CTP2A_3_10	2.96	CTP3_3_50	4.60	SU7_3_40	3.56
SU6_3_30	2.9	CTP2A_3_60	4.57	CTP3_2_10	3.53
SU5_3_20	2.89	CTP3_3_40	4.56	CTP3_3_60	3.53
CTP3_2_30	2.86	SU7_3_10	4.32	CTP2A_3_20	3.51
SU7_3_40	2.86	SU7_3_20	4.15	CTP3_2_20	3.47

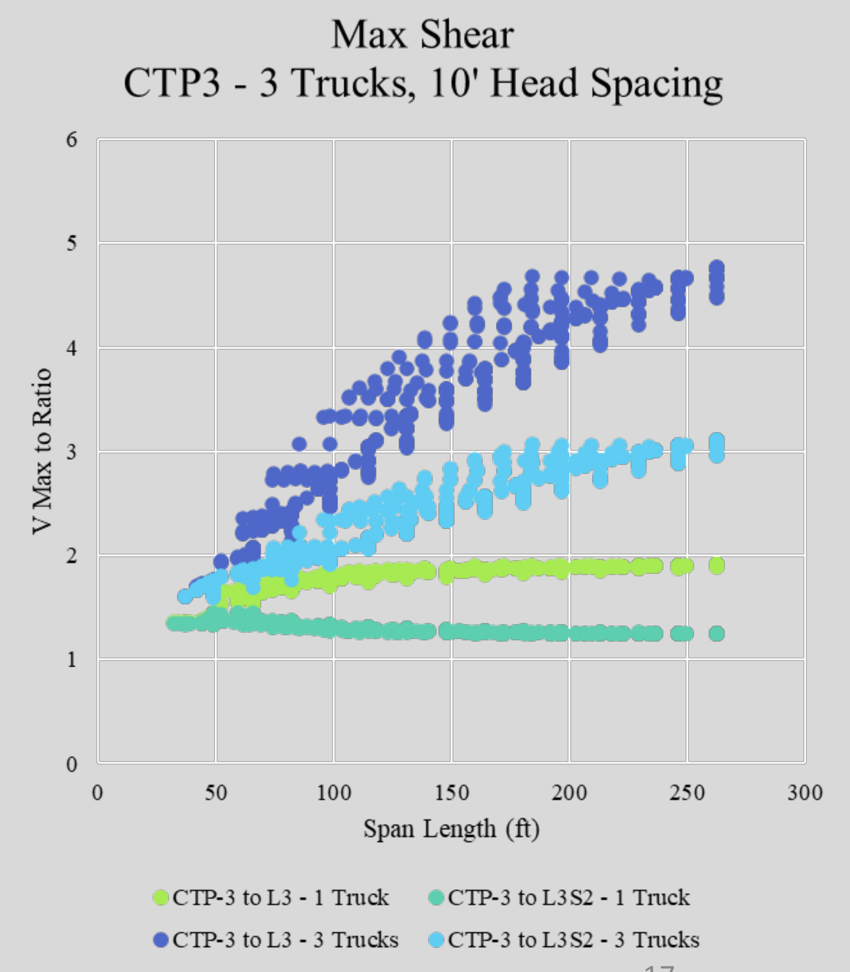
Ratios – Reference: OR Type 3S2 Legal

Maximum Positive Bending Moment		Maximum Negative Bending Moment		Maximum Shear	
Truck Type	*Ratio*	*Truck Type*	*Ratio*	*Truck Type*	*Ratio*
CTP3_3_10	2.85	CTP3_3_10	3.47	CTP3_3_10	3.11
CTP3_3_20	2.61	CTP2B_3_10	3.32	CTP3_3_20	2.96
SU7_3_10	2.55	CTP2B_3_20	3.27	CTP3_3_30	2.81
CTP3_3_30	2.39	CTP2A_3_10	3.24	SU7_3_10	2.66
SU6_3_10	2.37	CTP3_3_20	3.23	CTP3_3_40	2.64
SU7_3_20	2.36	CTP2B_3_30	3.22	CTP2B_3_10	2.60
CTP3_2_10	2.22	CTP2A_3_20	3.19	SU7_3_20	2.56
CTP2B_3_10	2.2	CTP2B_3_40	3.19	CTP3_3_50	2.47
SU6_3_20	2.19	CTP2A_3_30	3.15	CTP2A_3_10	2.47
SU7_3_30	2.17	CTP2B_3_50	3.13	SU6_3_10	2.45
SU5_3_10	2.18	CTP2A_3_40	3.11	SU7_3_30	2.45
CTP3_3_40	2.17	CTP3_3_30	3.10	CTP2B_3_20	2.43
Legal3S2_3_10	2.15	CTP2B_3_60	3.05	Legal3S2_3_10	2.38
CTP3_2_20	2.11	CTP2A_3_50	3.04	Legal33_3_10	2.36
Legal33_3_10	2.09	CTP3_3_40	3.00	SU6_3_20	2.35
CTP2A_3_10	2.06	CTP3_3_50	2.98	SU7_3_40	2.33
SU6_3_30	2.02	CTP3_3_60	2.97	CTP3_2_10	2.30
SU5_3_20	2.02	CTP2A_3_60	2.93	CTP3_3_60	2.30
CTP3_2_30	2.00	SU7_3_10	2.84	CTP2A_3_20	2.29
SU7_3_40	2.00	SU7_3_20	2.73	CTP3_2_20	2.26

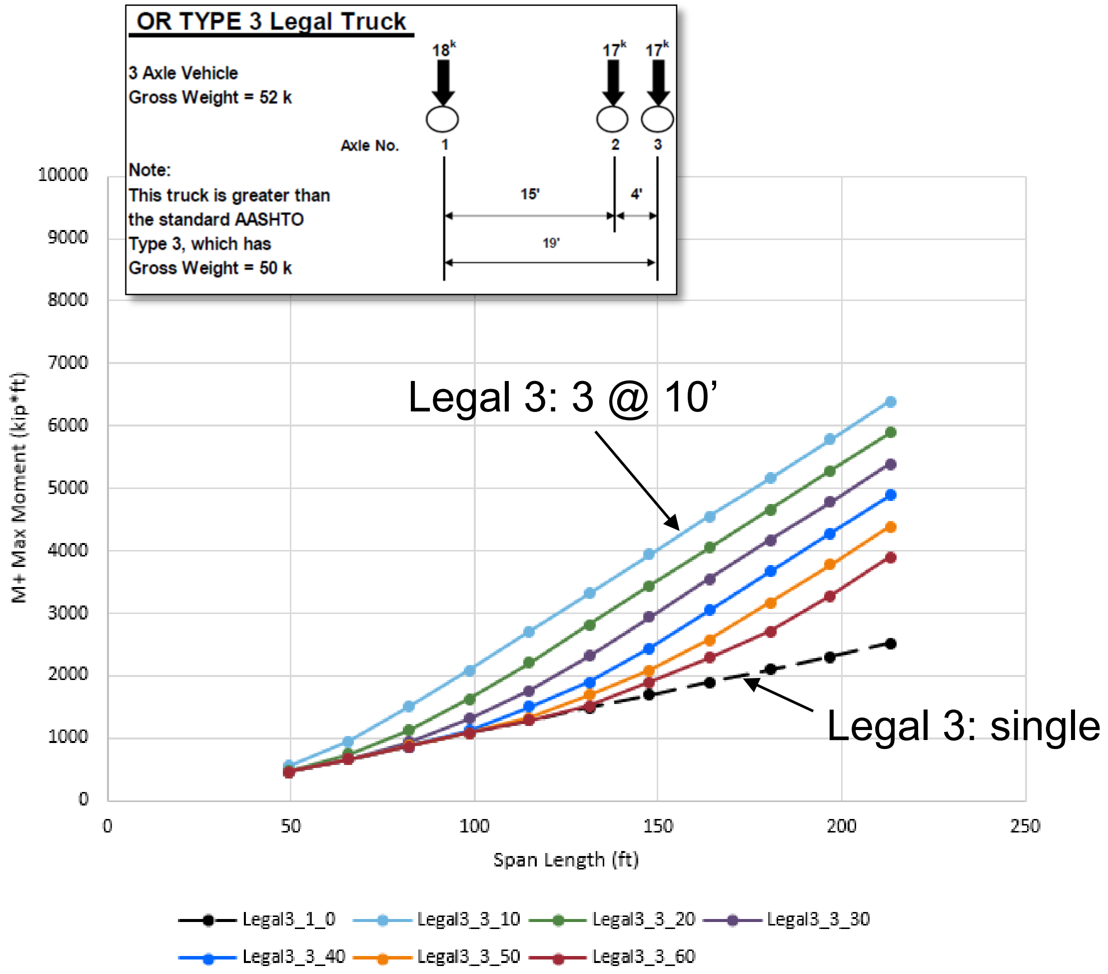
Variables studies – Ratio vs. span length

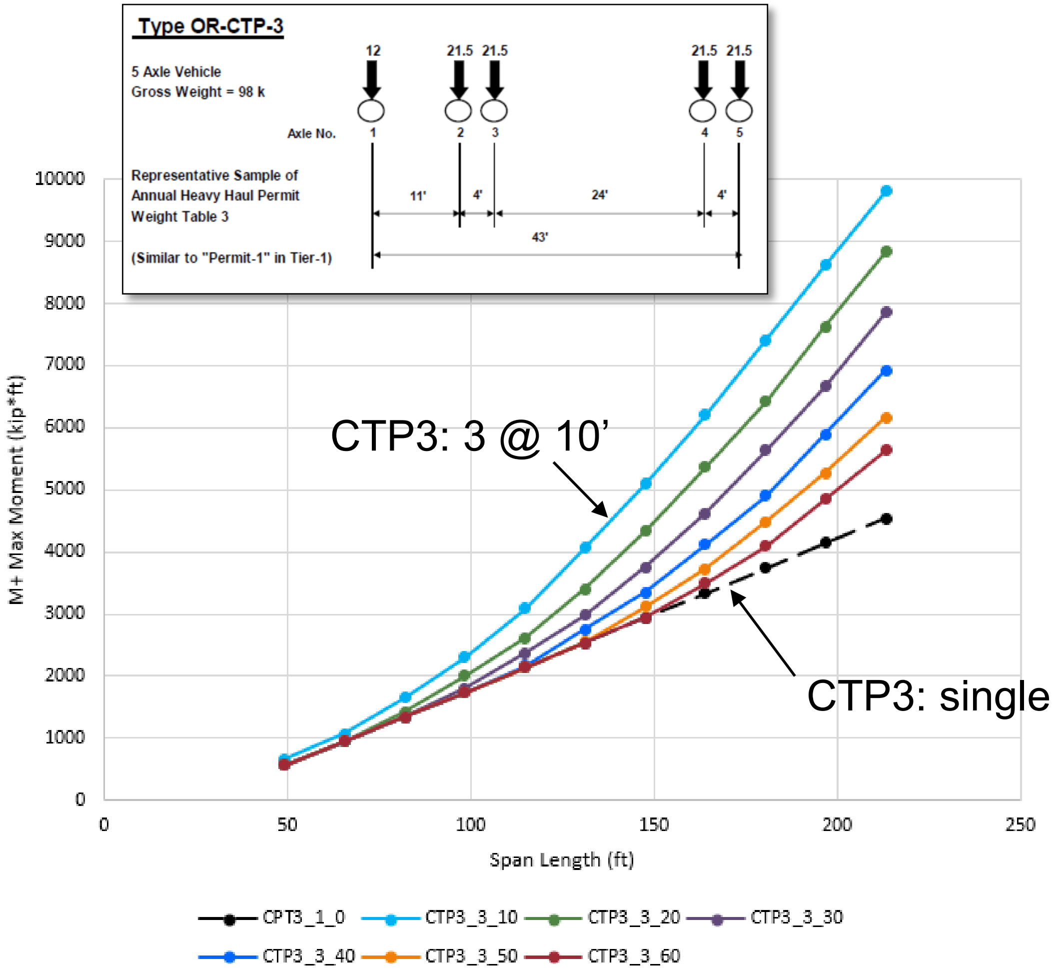






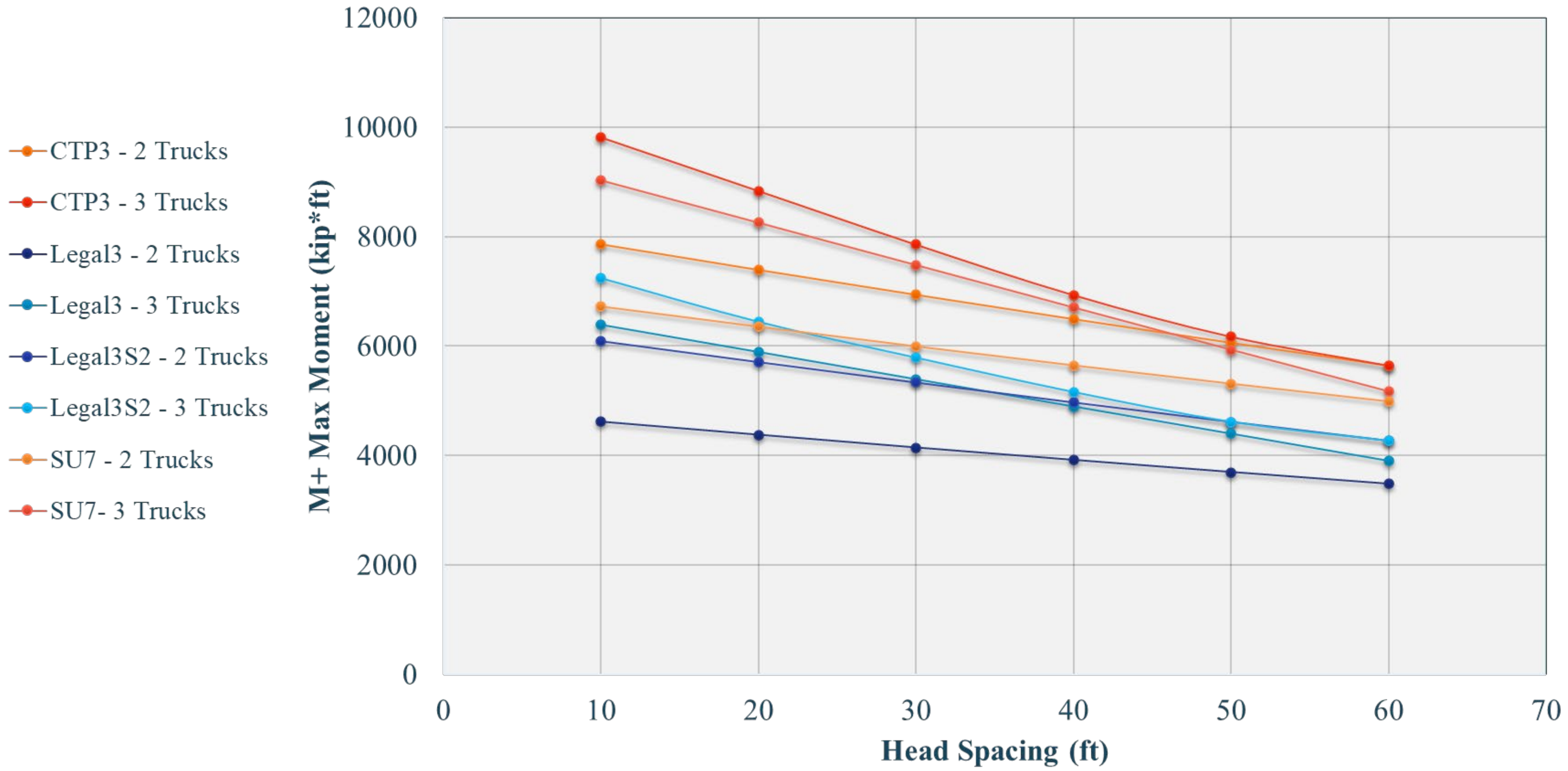
Variables studies – Effect of platooning on M^{+}_{max}





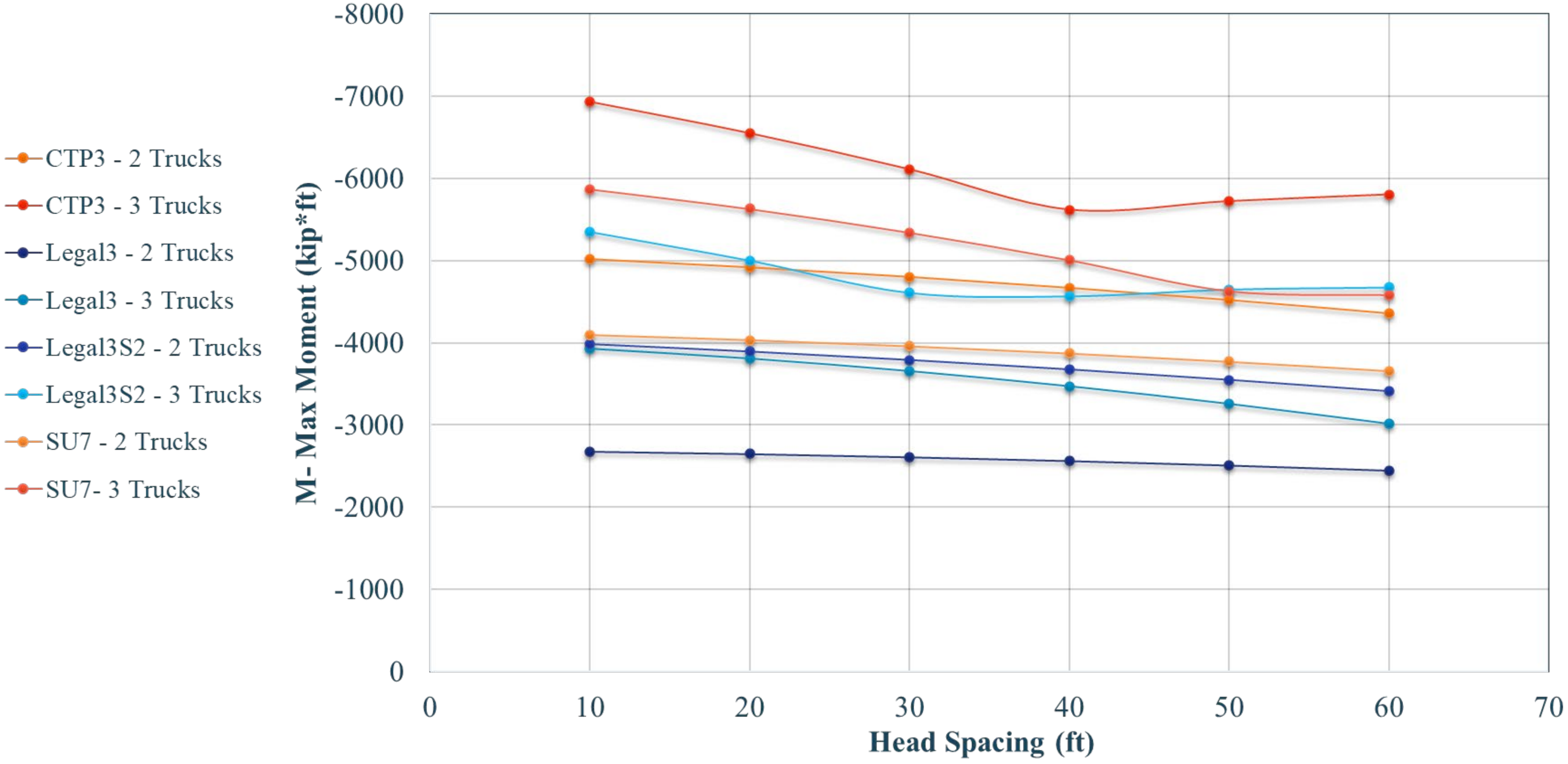
Variables studies – Effect of head spacing

Bridge 11 – Single-span, L = 213 ft (65 m)



Variables studies – Effect of head spacing (cont.)

Bridge 708 – Three-span, L = 262 – 262 – 213 ft (80 – 80 – 65 m)



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Case study 1 – Effect of head spacing

Ratios for single span bridges

(Ref.: OR Type 3S2 Legal)

(green)	Ratio < 1.10
(orange)	1.10 ≤ Ratio < 1.20
(red)	Ratio ≥ 1.20

Positive bending moment		Shear force	
Truck platoon configuration	Ratio	Truck platton configuration	Ratio
Legal3S2_3_10	1.221	Legal3S2_3_10	1.386
Legal3S2_2_10	1.220	Legal3S2_2_10	1.385
Legal3S2_2_50	1.001	Legal3S2_3_20	1.222
Legal3S2_2_60	1.001	Legal3S2_2_20	1.219
Legal3S2_3_60	1.001	Legal3S2_2_30	1.049
Legal3S2_2_40	1.000	Legal3S2_3_30	1.047
Legal3S2_3_40	1.000	Legal3S2_3_60	1.000
Legal3S2_3_50	1.000	Legal3S2_1_0	1.000
Legal3S2_2_20	1.000	Legal3S2_2_60	1.000
Legal3S2_2_30	1.000	Legal3S2_3_50	0.999
Legal3S2_1_0	1.000	Legal3S2_2_50	0.999
Legal3S2_3_30	1.000	Legal3S2_3_40	0.998
Legal3S2_3_20	1.000	Legal3S2_2_40	0.997

Case study 1 – Effect of head spacing (cont.)

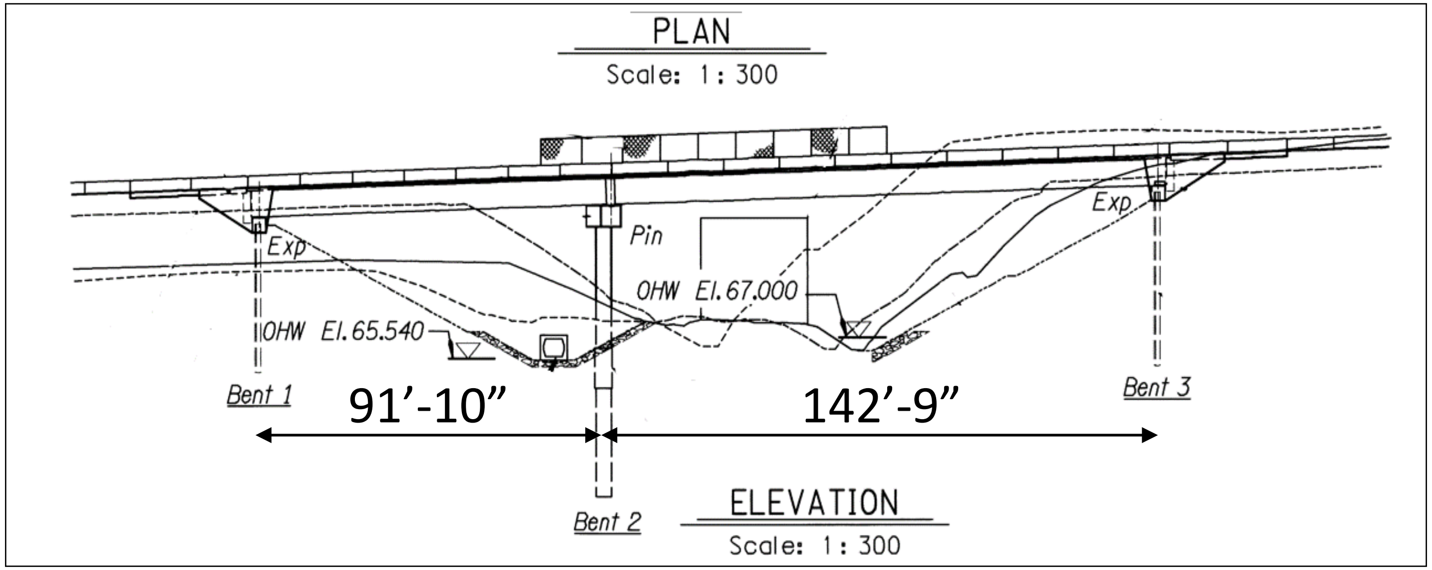
Ratios for three-span bridges

(Ref.: OR Type 3S2 Legal)

Green	Ratio < 1.10
Orange	1.10 ≤ Ratio < 1.20
Red	Ratio ≥ 1.20

Positive bending moment		Negative bending moment		Shear force	
Truck platoon configuration	Ratio	Truck platton configuration	Ratio	Truck platton configuration	Ratio
Legal3S2_2_10	1.034	Legal3S2_3_10	1.509	Legal3S2_3_10	1.391
Legal3S2_3_10	1.025	Legal3S2_2_10	1.374	Legal3S2_2_10	1.390
Legal3S2_2_40	1.001	Legal3S2_2_20	1.175	Legal3S2_3_20	1.184
Legal3S2_3_60	1.001	Legal3S2_3_20	1.175	Legal3S2_2_20	1.182
Legal3S2_3_20	1.000	Legal3S2_2_30	1.085	Legal3S2_3_30	1.045
Legal3S2_3_50	1.000	Legal3S2_3_30	1.085	Legal3S2_2_30	1.044
Legal3S2_2_60	1.000	Legal3S2_2_40	1.007	Legal3S2_2_40	1.018
Legal3S2_2_50	1.000	Legal3S2_3_40	1.007	Legal3S2_3_40	1.017
Legal3S2_2_30	1.000	Legal3S2_1_0	1.000	Legal3S2_2_60	1.000
Legal3S2_3_40	1.000	Legal3S2_2_50	1.000	Legal3S2_1_0	1.000
Legal3S2_3_30	1.000	Legal3S2_3_50	1.000	Legal3S2_2_50	0.998
Legal3S2_1_0	1.000	Legal3S2_2_60	1.000	Legal3S2_3_50	0.998
Legal3S2_2_20	1.000	Legal3S2_3_60	1.000	Legal3S2_3_60	0.998

Case study 2 – Rating factor analysis



Capacity — Dead Load

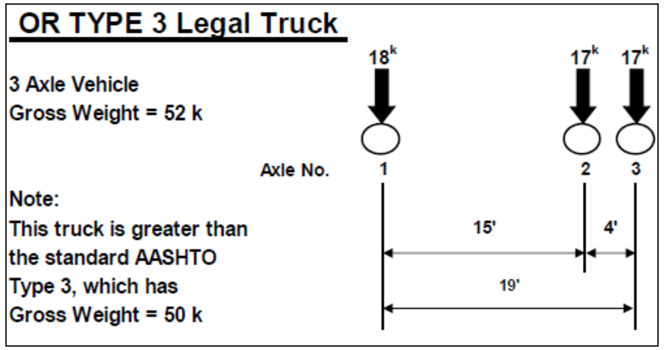
LRFR Strength Limit State:

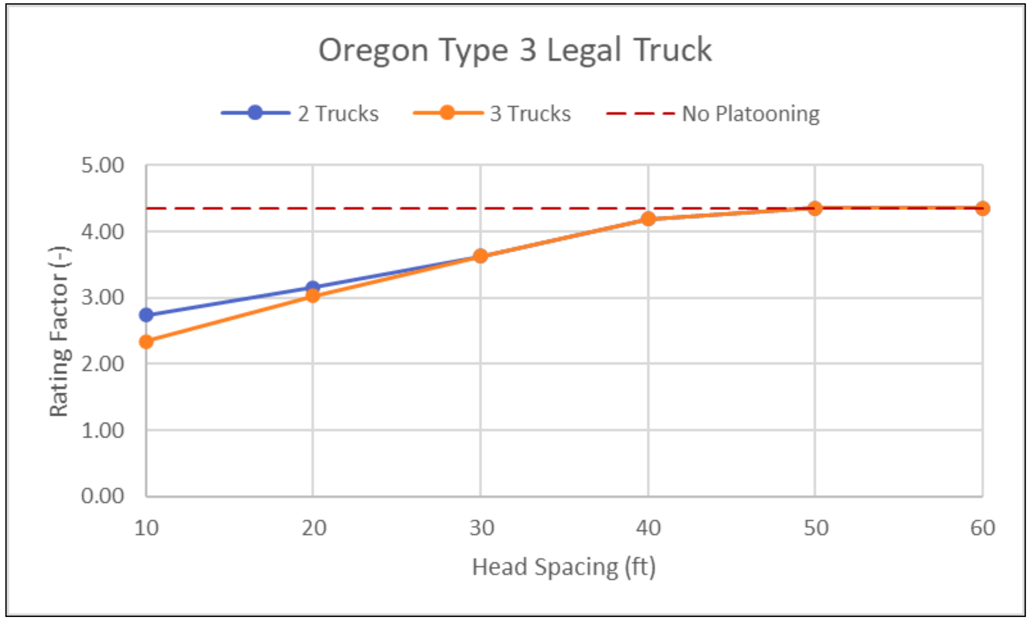
$$RF = \frac{\phi_c \cdot \phi_s \cdot \phi \cdot (R_n) - (\gamma_{DC}) \cdot (DC) - (\gamma_{DW}) \cdot (DW)}{(\gamma_L) \cdot (LL + IM)}$$ (MBE 6A.4.2.1-1)

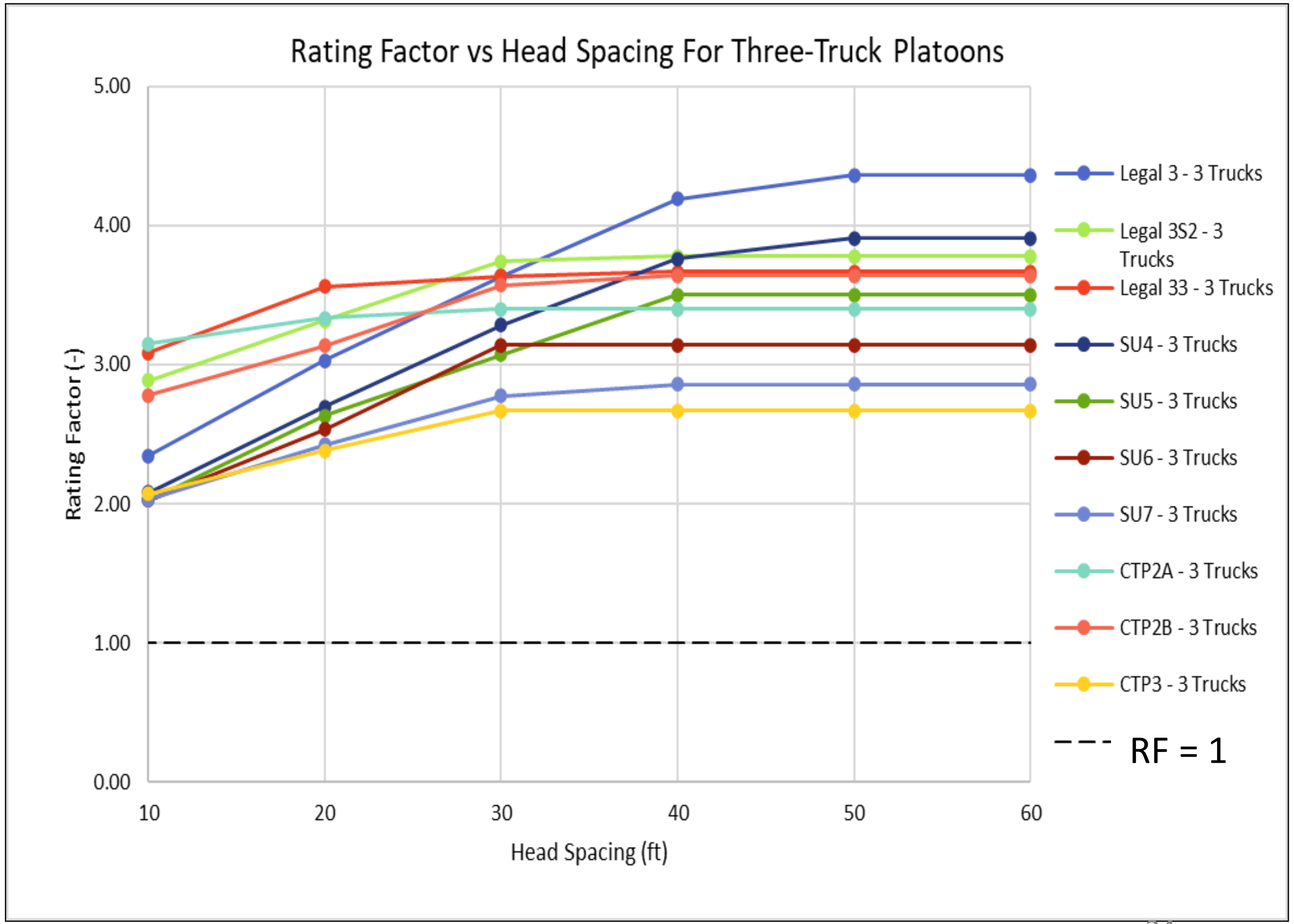
Multiply with ratio — Live Load

Rating Factor Calculations:	Type 3 Legal		
Head Spacing =	0	10	20
Location =	0.5L	0.5L	0.5L
RF =	4.36	4.36	4.36
ϕ_c =	1.00	1.00	1.00
ϕ_{sf} =	1.00	1.00	1.00
ϕ =	1.00	1.00	1.00
R_n =	6659.26	6659.26	6659.26
γ_{DC} =	1.25	1.25	1.25
DC (ft-kips) =	1748.90	1748.9	1748.9
γ_{DW} =	1.25	1.25	1.25
DW (ft-kips) =	63.30	63.30	63.30
γ_L =	1.40	1.40	1.40
LL (ft-kips)=	1007.80	1007.80	1007.80
LL (ft-kips)=	903.33	903.33	903.33
IM =	1.10	1.10	1.10
Girder Weight (ft-kips) =	796.10	796.10	796.10
Diaphragms (ft-kips) =	108.80	108.80	108.80
Buildup & Deck (ft-kips) =	844.00	844.00	844.00
Rails (ft-kips) =	63.30	63.30	63.30
1 Truck - Platooning Ratio =	1.00	0.00	0.00
2 Truck - Platooning Ratio =	0.00	1.59	1.38
3 Truck - Platooning Ratio =	0.00	1.86	1.44
1 Truck - Platooning LL (ft-kips) =	1007.80	0.00	0.00
2 Truck - Platooning LL (ft-kips) =	0.00	1602.40	1390.76
3 Truck - Platooning LL (ft-kips) =	0.00	1874.51	1451.23
1 Truck - Platooning RF =	4.36	0.00	0.00
2 Truck - Platooning RF =	0.00	2.74	3.16
3 Truck - Platooning RF =	0.00	2.34	3.03

Case study 2 – Rating factor analysis (cont.)

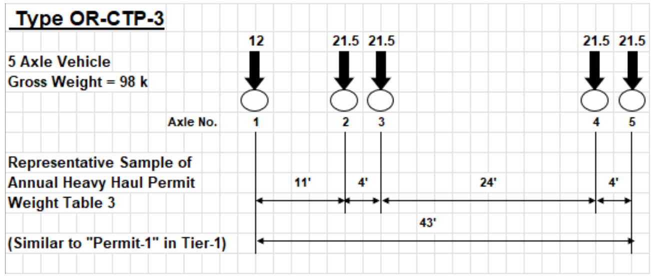






Summary and conclusions

- 360,269 moving load analysis performed, considering:
  - HL-93 design, OR Legal, OR CTP, OR STP, and FAST Act EV loads
  - 749 single-, two-, and three-span bridges (line girder analysis)
- Significant increases in the internal forces observed, e.g., for CTP-3/OR Type 3 Legal-ratio:
  - Max. pos. bending moment: Max. ratio = 4.08 3 - OR CTP-3 @ 10 ft
  - Max. neg. bending moment: Max. ratio = 5.10 3 - OR CTP-3 @ 10 ft
  - Max. shear force: Max. ratio = 4.77 3 - OR CTP-3 @ 10 ft
- Effect of truck platooning worst on longer spans
- To really know, load rating is necessary (with assumptions…)



- Future work: Estimate live load factors for truck platoons via simulation; Network study using automated load rating; Evaluate impact on design of new bridges, e.g., I-5 replacement

SPR-848 Products

- Final report (pending)
- Technote (pending)
- 360,269 text files containing moving load analysis results
- Spreadsheet with max. internal forces and load effect ratios:

Bridge_Number	Number_of_Spans	Span_1_Length	Span_2_Length	Span_3_Length	Truck_Number	Truck_Type	Number_of_Trucks	Head_Spacing	M_Max_Pos_EB	V_M_Max_Pos_EB	x_M_Max_Pos_EB	M_Max_Neg_EB	V_M_Max_Neg_EB	x_M_Max_Neg_EB	V_Max_EB	M_V_Max_EB	x_V_Max_EB	M_Max_Pos_S1	V_M_Max_Pos_S1	x_M_Max_Pos_S1	M_Max_Neg_S1	V_M_Max_Neg_S1	x_M_Max_Neg_S1	V_L_S1	M_V_L_S1	x_V_L_S1	V_R_S1	M_V_R_S1	x_V_R_S1	M_M Pos_
1	1	49.2126			0	No Trucks	0	0	302.284	-0.40864	25	0	0	0	24.5914	1.008E-12	0	302.28	-0.4086	25	0	0	0	24.591	1E-12	0	-23.409	4E-13	49.213	
1	1	49.2126			1	HL93Tandem	1	0	543.369	-1.34944	24	-2.32E-11	-2.158E-13	24	-46.0062	-2.155E-13	49.2126	543.37	-1.3494	24	-2E-11	-2E-13	24	46.006	1E-13	0	-46.006	-2E-13	49.213	
1	1	49.2126			10	HL93Tandem	2	50	543.365	-1.34228	24	-4.604E-11	-4.596E-13	23	-46.0473	-4.583E-13	49.2126	543.37	-1.3423	24	-5E-11	-5E-13	23	46.047	-5E-13	0	-46.047	-5E-13	49.213	
1	1	49.2126			100	SU7	3	40	688.255	5.15302	24	-3.197E-11	-8.793E-13	23	-57.0278	7.188E-12	49.2126	688.26	5.153	24	-3E-11	-9E-13	23	57.028	5E-12	0	-57.028	7E-12	49.213	
1	1	49.2126			101	SU7	2	50	688.185	5.13021	24	-2.329E-11	-2.558E-13	24	-57.0534	8.108E-12	49.2126	688.19	5.1302	24	-2E-11	-3E-13	24	57.053	-4E-12	0	-57.053	8E-12	49.213	
1	1	49.2126			102	SU7	3	50	688.32	-11.8167	24	-3.477E-11	-2.665E-13	24	-57.0189	1.787E-12	49.2126	688.32	-11.817	24	-3E-11	-3E-13	24	57.019	2E-12	0	-57.019	2E-12	49.213	
1	1	49.2126			103	SU7	2	60	688.166	-11.7969	24	-2.454E-11	4.743E-13	24	-56.8897	3.551E-12	49.2126	688.17	-11.797	24	-2E-11	5E-13	24	56.89	-6E-12	0	-56.89	4E-12	49.213	
1	1	49.2126			104	SU7	3	60	688.247	-11.8073	24	-3.76E-11	-6.288E-13	23	-57.0541	-5.044E-12	49.2126	688.25	-11.807	24	-4E-11	-6E-13	23	57.054	-6E-12	0	-57.054	-5E-12	49.213	
1	1	49.2126			105	EV2	1	0	538.718	-25.3961	28	-3.9E-11	-2.878E-13	24	-50.1547	-3.462E-13	49.2126	538.72	-25.396	28	-4E-11	-3E-13	24	50.155	-6E-13	0	-50.155	-3E-13	49.213	
1	1	49.2126			106	EV2	2	10	718.674	6.6481	28	-5.462E-11	-1.332E-12	23	-71.0277	3.337E-12	49.2126	718.67	6.6481	28	-5E-11	-1E-12	23	71.028	2E-12	0	-71.028	3E-12	49.213	
1	1	49.2126			107	EV2	3	10	736.255	9.13648	29	-6.966E-11	-1.375E-12	23	-75.9777	-1.996E-13	49.2126	736.26	9.1365	29	-7E-11	-1E-12	23	75.978	5E-12	0	-75.978	-2E-13	49.213	
1	1	49.2126			108	EV2	2	20	583.131	-14.9349	25	-6.06E-11	-7.727E-13	24	-59.8538	-5.208E-12	49.2126	583.13	-14.935	25	-6E-11	-8E-13	24	59.854	3E-13	0	-59.854	-5E-12	49.213	
1	1	49.2126			109	EV2	3	20	583.335	-14.9559	25	-8.205E-11	-1.908E-12	23	-59.7463	5E-12	49.2126	583.34	-14.956	25	-8E-11	-2E-12	23	59.746	4E-13	0	-59.746	5E-12	49.213	
1	1	49.2126			11	HL93Tandem	3	50	543.318	-1.26399	24	-7.07E-11	-1.737E-12	23	-46.0197	3.089E-13	49.2126	543.32	-1.264	24	-7E-11	-2E-12	23	46.02	-6E-13	0	-46.02	3E-13	49.213	
1	1	49.2126			110	EV2	2	30	538.249	8.02612	28	-6.661E-11	-4.476E-13	24	-52.9286	-1.426E-12	49.2126	538.25	8.0261	28	-7E-11	-4E-13	24	52.929	-1E-13	0	-52.929	-1E-12	49.213	
1	1	49.2126			111	EV2	3	30	538.542	-7.84189	21	-9.428E-11	-2.345E-12	23	-53.0177	6.862E-12	49.2126	538.54	-7.8419	21	-9E-11	-2E-12	23	53.018	-1E-12	0	-53.018	7E-12	49.213	
1	1	49.2126			112	EV2	2	40	538.67	8.08252	28	-7.233E-11	-1.066E-13	24	-50.1605	-1.914E-12	49.2126	538.67	8.0825	28	-7E-11	-1E-13	24	50.161	-2E-15	0	-50.161	-2E-12	49.213	
1	1	49.2126			113	EV2	3	40	538.528	-7.8401	21	-1.058E-10	-6.715E-13	24	-50.1457	-8.904E-14	49.2126	538.53	-7.8401	21	-1E-10	-7E-13	24	50.146	5E-14	0	-50.146	-9E-14	49.213	
1	1	49.2126			114	EV2	2	50	538.512	8.06136	28	-7.899E-11	-1.95E-12	23	-50.0542	1.002E-12	49.2126	538.51	8.0614	28	-8E-11	-2E-12	23	50.054	-8E-13	0	-50.054	1E-12	49.213	